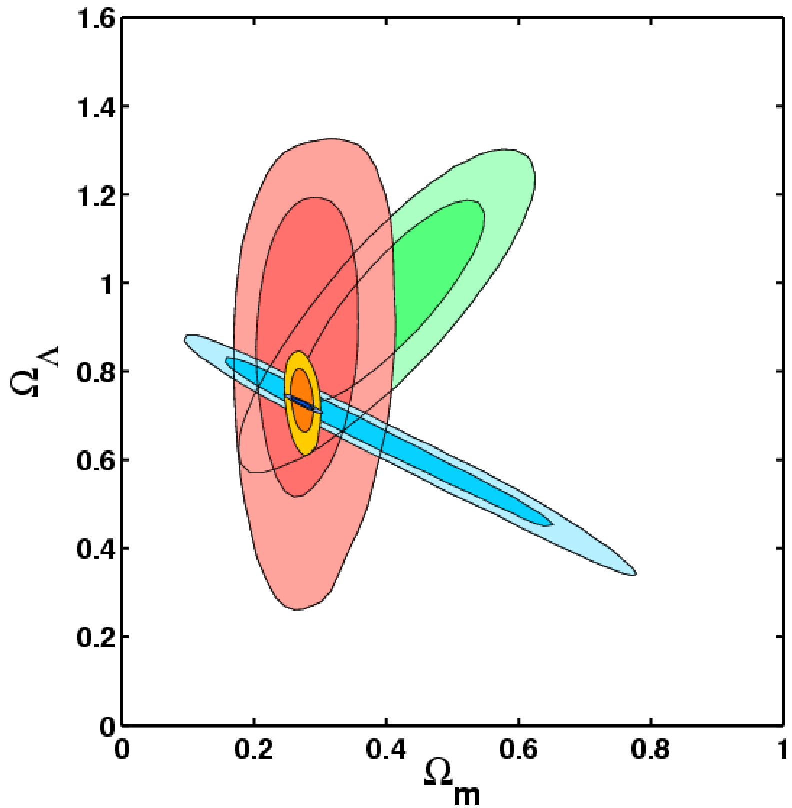
Probing dark energy with absolute distance measurements to clusters

Steve Allen, KIPAC (Stanford/SLAC)



In collaboration with:

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Dark Energy 1:

The origin of cosmic acceleration (dark energy) is widely viewed as the biggest current question in physics.

<u>What observational routes do we have to study it?</u>

CMB (WMAP,Planck), SNIa (LST,JDEM), BAO (LST,SKA,JDEM), weak lensing (LST,SKA,JDEM), cluster counts (X-ray,SZ,LST)

+ absolute distance measurements to clusters (Con-X) ← (space only).

These methods have different strengths/weaknesses and are sensitive to dark energy in essentially two different ways:

1) absolute distances/expansion history (CMB,SN,BAO,cluster distance)
2) growth of structure (weak lensing, cluster counts)

Note no single technique will pin down the nature of DE (i.e. increase current knowledge x10). Techniques will need to be combined to do this (so good idea to look for complementary methods).

Dark Energy 2:

This talk will concentrate on the contribution of Con-X to cosmology/DE studies via absolute distance measurements to galaxy clusters.

There are actually two techniques to measure distances:

1) measurements of the baryonic mass fraction + evolution.
2) combination of observed (radio/sub-mm) and predicted (X-ray) Sunyaev-Zel'dovich (SZ) effect.

We will discuss methods, current constraints, an observing strategy with Con-X, and (David's talk) the predicted constraints.

(See Alexey's talk for discussion of Con-X contribution to cluster counting/growth of structure work.)

Method 1: constraining dark matter and dark energy via measurements of the baryonic mass fraction in clusters

Allen et al 2002,2005,2007

Ettori et al 2003, LaRoque et al 2006

Rapetti et al. 2005, 2007

Constraining Ω_m with f_{gas} measurements

BASIC IDEA (White & Frenk 1991): Galaxy clusters are so large that their matter content should provide a fair sample of matter content of Universe.

For relaxed clusters: X-ray data → precise total mass measurements
→ (very) precise X-ray gas mass measurements

If we define:

$$f_{gas} = \frac{\text{X-ray gas mass}}{\text{total cluster mass}} \qquad f_{star} = 0.16 h_{70}^{0.5} f_{gas}$$

eg Lin & Mohr 04
Fukugita et al '98

Then:

$$f_{baryon} = f_{star} + f_{gas} = f_{gas}(1 + 0.16 h_{70}^{0.5})$$

Since clusters provide ~ fair sample of Universe $f_{baryon} = b\Omega_b/\Omega_m$

$$\Omega_m = \frac{b\Omega_b}{f_{baryon}} = \frac{b\Omega_b}{f_{gas}(1+0.16 h_{70}^{0.5})}$$

The bias (depletion) factor

Simulations:

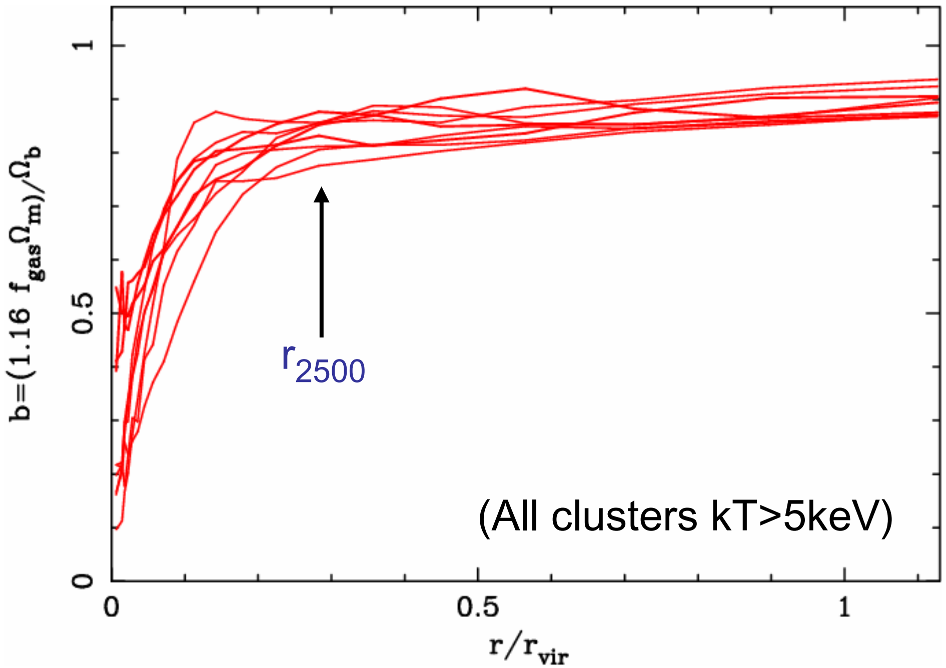
$$f_{\mathrm{baryon}} = b\frac{\Omega_b}{\Omega_m}$$

For r~0.25r_{vir} (Chandra obs.)

b = 0.83±0.09

(non-radiative simulations + 10% systematic uncertainty)

Eke et al 98



Simulations indicate that baryonic mass fraction in clusters is slightly lower than mean value for Universe as a whole. (Some gas is lifted beyond the virial radius by shocks e.g. Evrard '90, Thomas & Couchman '92, Navarro & White '93; NFW '95 etc ….)

Confirmed by recent simulations (e.g. Crain et al. astro-ph/0610602).

The current Chandra data

Chandra observations of 42 X-ray luminous, dynamically relaxed clusters:

$0.06<z<1.07$ $L_X>10^{45}h_{70}^{-2}$ erg/s $kT>5$keV

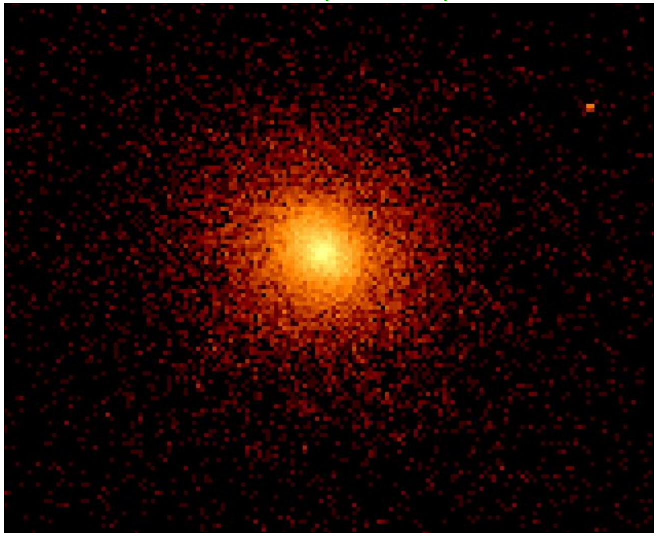
All have regular X-ray morphology, sharp central X-ray surface brightness peak, minimal X-ray isophote centroid variation. (X-ray morphological selection only)

MACS SURVEY
(Ebeling et al. ’01,‘07):

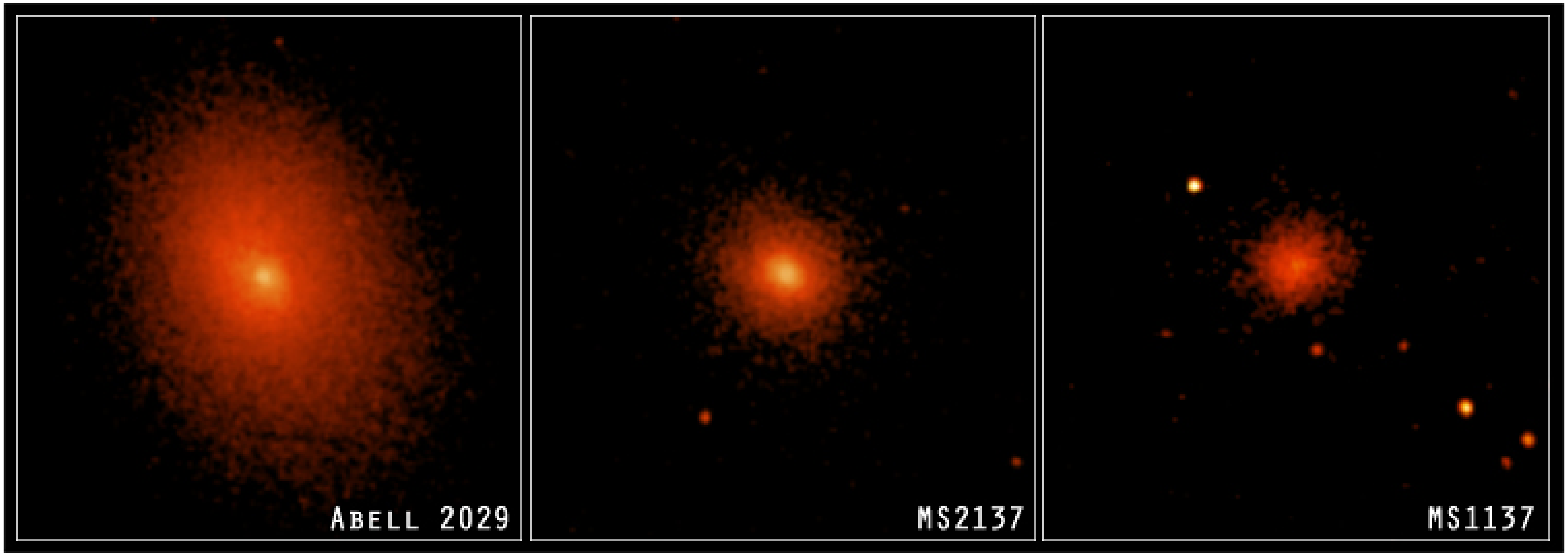
120 clusters at $z>0.3$ with $L_X>10^{45}$erg/s (>30x improvement over previous samples). Chandra snapshot programs lead by Leon van Speybroeck and Harald Ebeling.

This is the primary new data set for our growth of structure studies, but also provides bulk of relaxed clusters known at $z>0.3$.

MACS1423+24 (z=0.54) 120ks

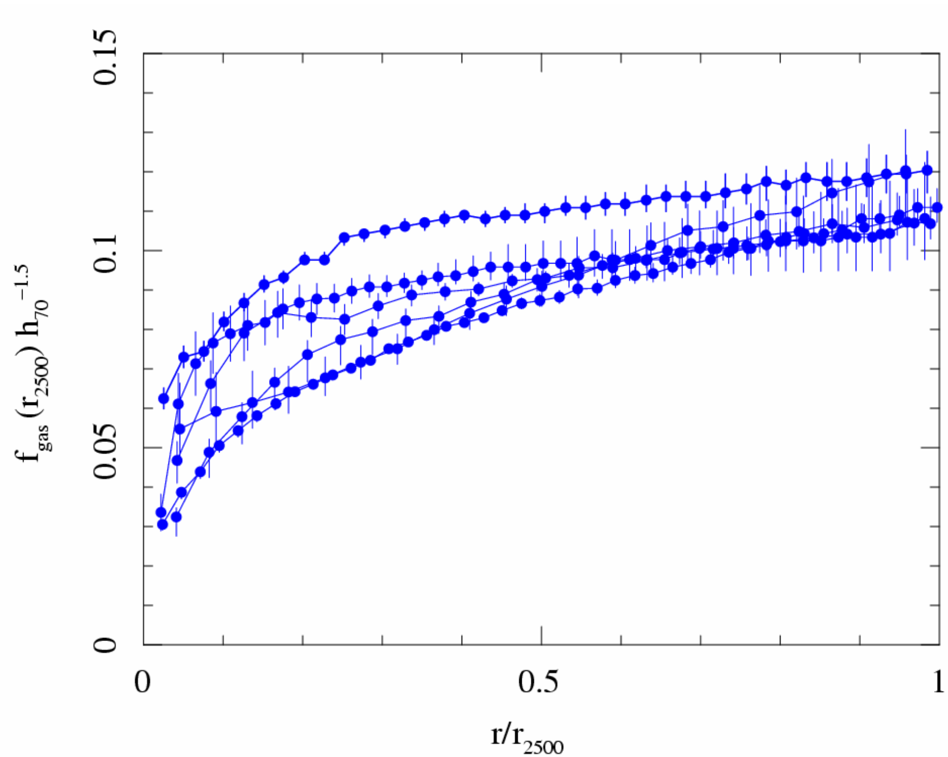


The Chandra data



The most dynamically relaxed, highly X-ray luminous clusters spanning the redshift range 0<z<1.1 (lookback time of 8Gyr)

Chandra results on f_{gas}(r)



6 lowest redshift relaxed clusters (0<z<0.15) :

f_{gas}(r) → approximately universal value at r_{2500}

Fit constant value at r_{2500}

$f_{gas}(r_{2500})=(0.113\pm0.003)h_{70}^{-1.5}$

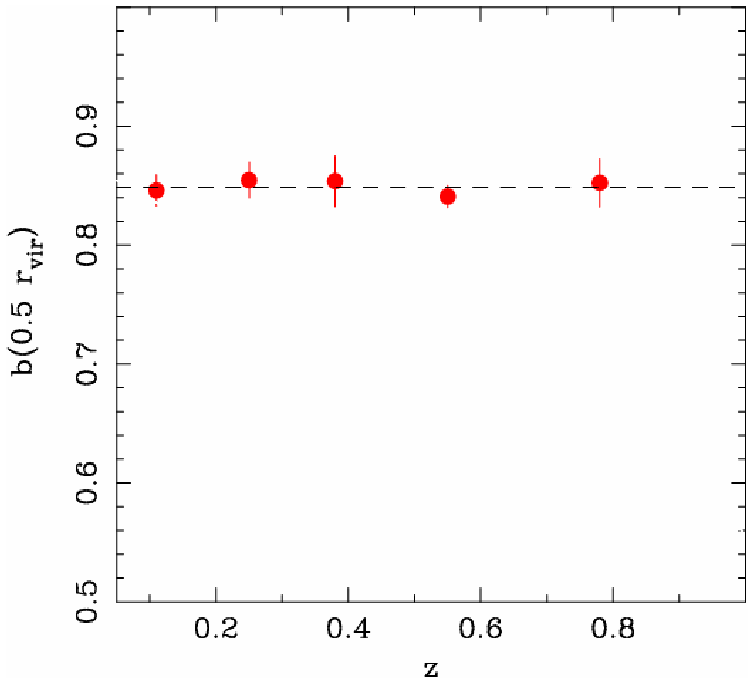
For $\Omega_b\, h^2=0.0214\pm0.0020$ (Kirkman et al. '03), h=0.72±0.08 (Freedman et al. '01), b=0.83±0.09 (Eke et al. 98 +10% allowance for systematics in calibration/modelling)

$$\Omega_m = \frac{(0.83\pm0.09)(0.0437\pm0.0041)h_{70}^{-0.5}}{(0.113\pm0.003)(1+[0.16\pm0.05]h_{70}^{0.5})} = 0.27\pm0.04$$

Constraining dark energy with f_{gas} measurements

(Sisaki '96) The measured f_{gas} values depend upon assumed distances to clusters as $f_{gas} \propto d^{1.5}$. This introduces apparent systematic variations in $f_{gas}(z)$ depending on differences between reference cosmology and true cosmology.

What do we expect to observe?



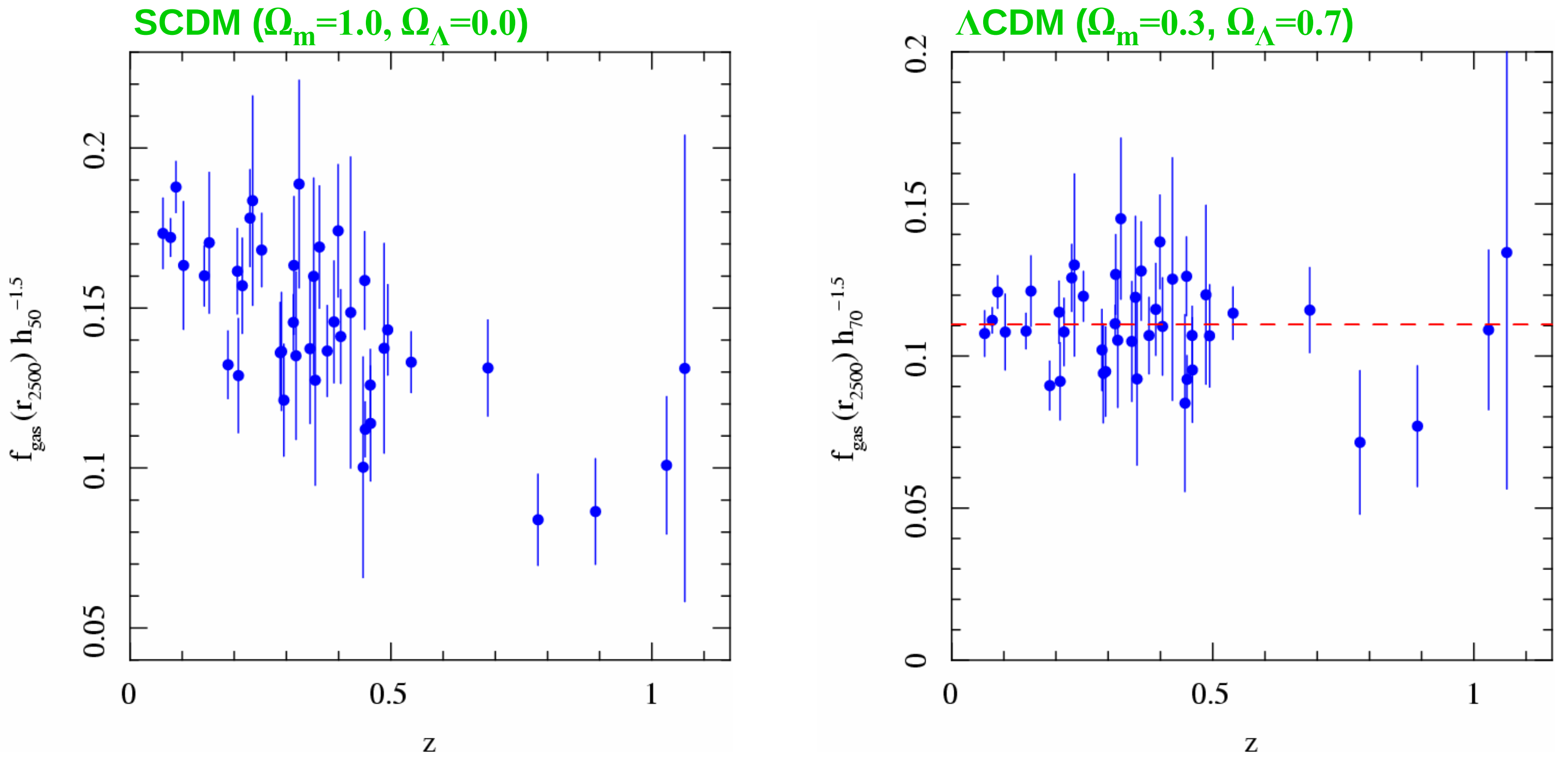
Simulations: Eke et al '98

Available non-radiative simulations for large (kT>5keV) relaxed clusters suggest little/no evolution of bias factor within $0.5r_{vir}$ for z<1.

So we expect the observed $f_{gas}(z)$ values to be approx. constant with z.

(See also Crain et al. 2006)

Chandra results on $f_{gas}(z)$



Brute-force determination of $f_{gas}(z)$ for two reference cosmologies:

→ Inspection clearly favours ΛCDM over SCDM cosmology.

To quantify: fit ΛCDM data with model which accounts for apparent variation in $f_{gas}(z)$ as underlying cosmology is varied $(\Omega_m,\Omega_\Lambda)$ → find model that provides best fit to data.

$$f_{gas}(z) = \frac{b\Omega_b}{(1+0.16\sqrt{h_{70}})\Omega_m}\left[\frac{d_A^{\;LCDM}(z)}{d_A^{\;model}(z)}\right]^{1.5}$$

Allowances for systematic uncertainties

Our full analysis includes a comprehensive and conservative treatment of potential sources of systematic uncertainty.

1) The bias factor (calibration, simulation physics, gas clumping etc.)

$b(z)=b_0(1+\alpha_b z)$: 10% Gaussian prior on b_0 (as before: modelling + calibration)
20% uniform prior on b_0 (simulation physics)
10% uniform prior on α_b (simulation physics)

2) Baryonic mass in stars: define $s= f_{star}/f_{gas} =0.16h_{70}^{0.5}$

$s(z)=s_0(1+\alpha_s z)$: 30% Gaussian uncertainty in s_0 (observational uncertainty)
20% uniform prior on α_s (observational uncertainty)

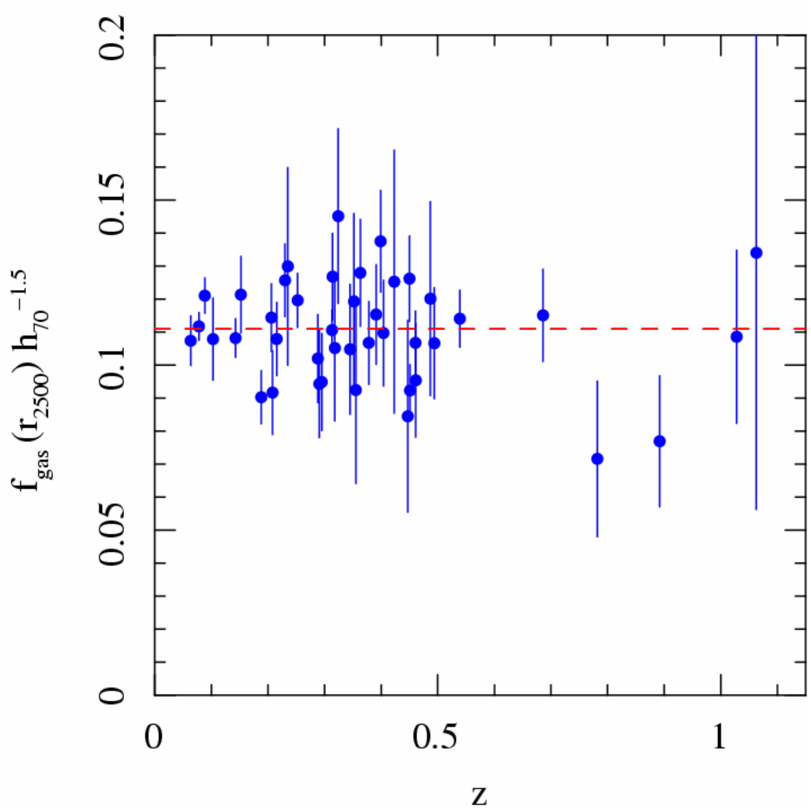
3) Non-thermal pressure support in gas: (mag fields, bulk motions)

$\gamma= M_{true}/M_{X\text{-}ray}$: 10% uniform prior $1<\gamma<1.1$ (eg Nagai et al 2006)

With these (conservative) allowances for systematics

Model:

$$f_{gas}(z) = \frac{\gamma b(z)\Omega_b}{(1+s(z))\Omega_m}\left[\frac{d_A^{\,LCDM}(z)}{d_A^{\,model}(z)}\right]^{1.5}$$



Results (ΛCDM)

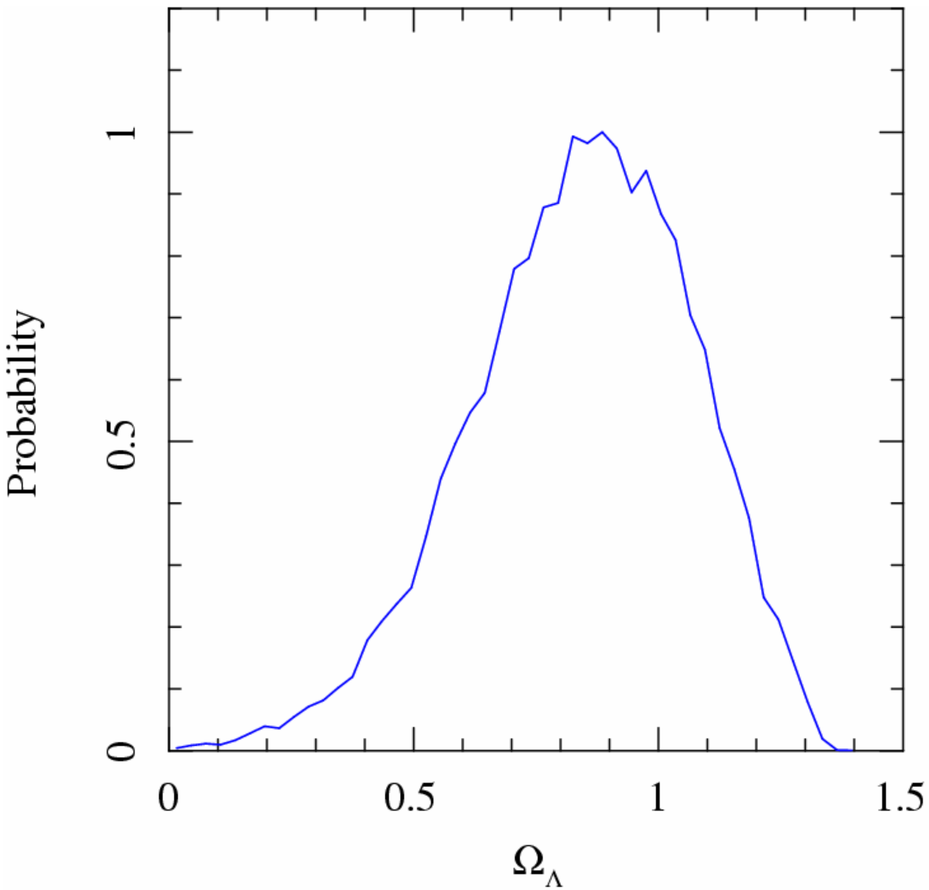
Full allowance for systematics + standard priors:
($\Omega_b h^2$=0.0214±0.0020, h=0.72±0.08, b=0.83±0.09)

Best-fit parameters (ΛCDM):

Ω_m=0.28±0.05, Ω_Λ=0.86±0.22

(Note also good fit: χ^2=41.7/40)

Marginalized results on dark energy (ΛCDM)



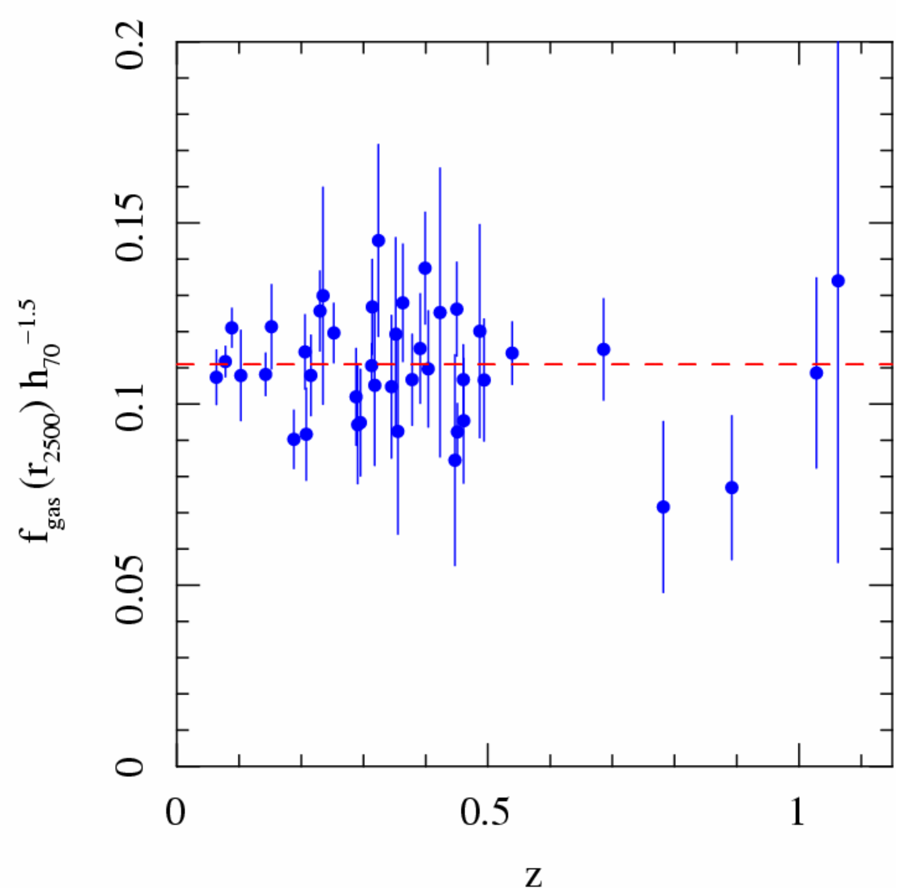
Including conservative allowances for systematic uncertainties and standard priors on $\Omega_b h^2$=0.0214±0.0020, h=0.72±0.08 (though insensitive to these priors).

Ω_Λ = 0.86±0.22

Detection of effects of dark energy at ~4σ (~99.99%) level. Comparable precision to SNIa studies.

The Chandra f_{gas}(z) data – like SNIa data (which also measure distance as a function of redshift) – show that the Universe is accelerating. The physics is both independent of SNIa and simple!

The scatter in the $f_{gas}(z)$ data is low



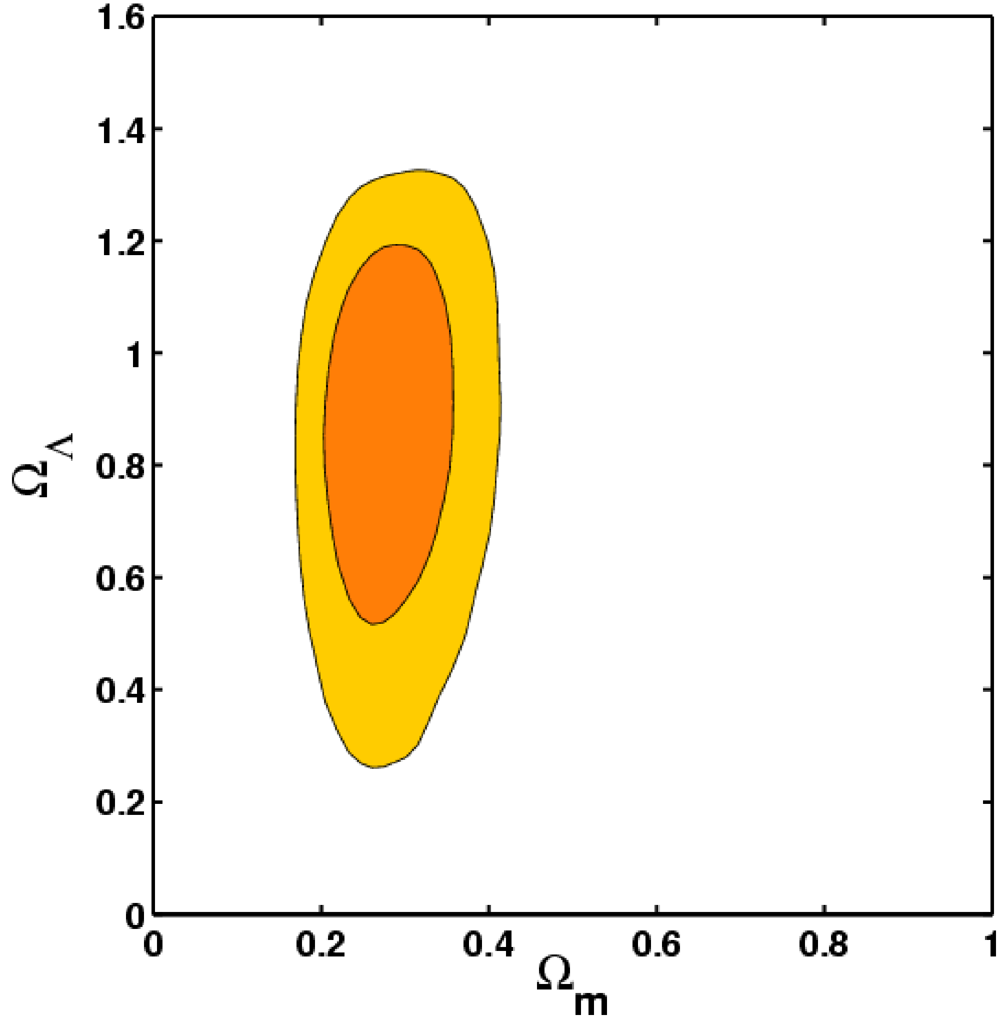
Acceptable χ^2 even though rms scatter about the best-fit model is only 10% in fgas, corresponding to only 6.6% in distance.

Weighted mean scatter only 5% in fgas (3.3% distance). For SNIa, systematic scatter is detected at ~7% level (distance).

No sign as yet of systematic scatter in $f_{gas}(z)$ data. Simulations of Crain et al (2006) suggest scatter should be at few % level in fgas $\rightarrow$ method offers prospect to probe cosmic acceleration to high precision with Con-X

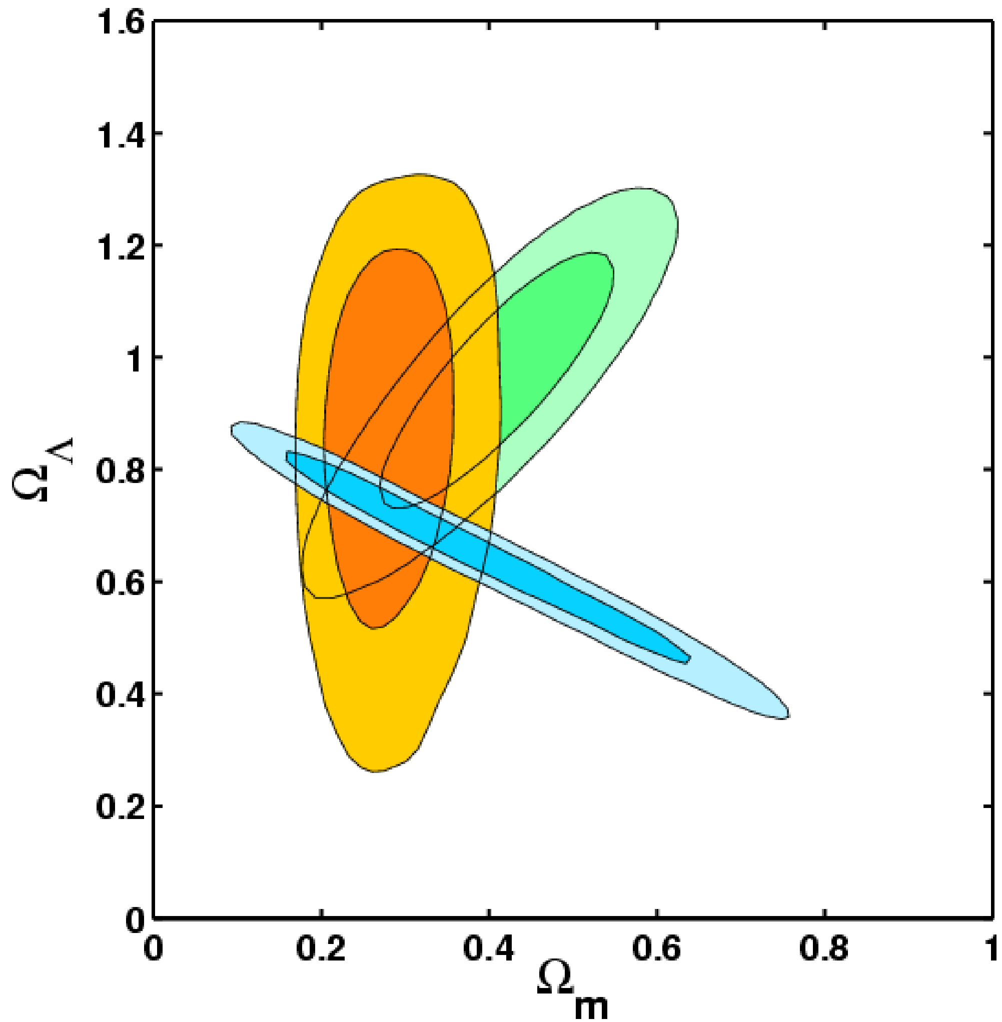
Comparison with other current data

Comparison of independent constraints (ΛCDM)



f_{gas} analysis: 42 clusters including standard $\Omega_b h^2$, and h priors and full systematic allowances

Comparison of independent constraints (ΛCDM)



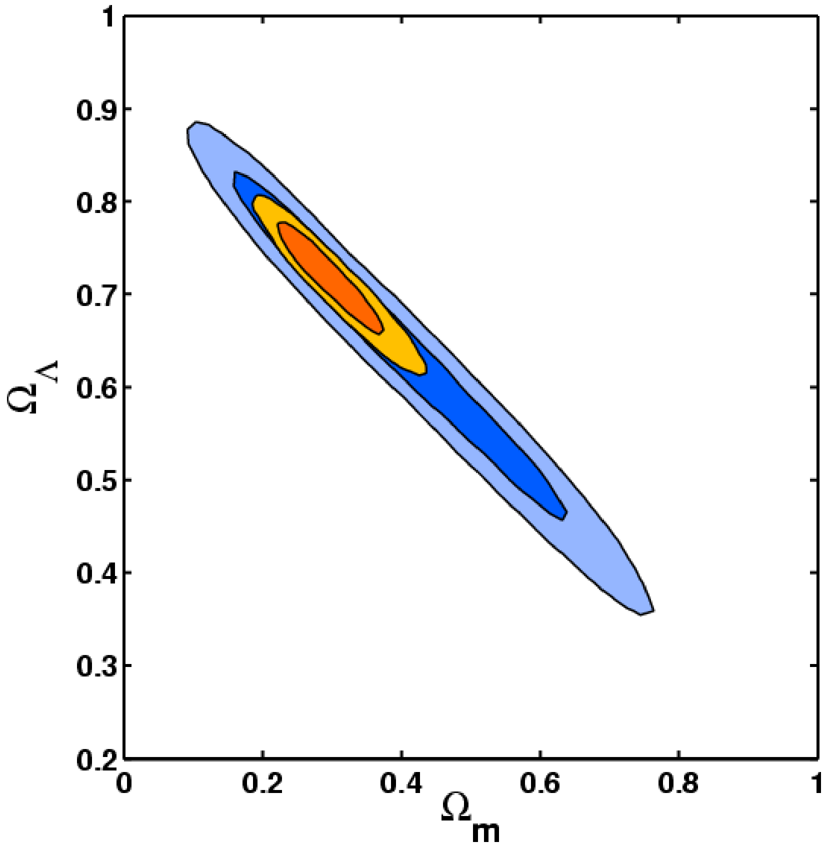
f_{gas} analysis: 42 clusters including standard $\Omega_b h^2$, and h priors and full systematic allowances

CMB data (WMAP3 + prior 0.4<h<2.0)

Supernovae data from Riess et al. '04 (Gold sample) and Astier et al '05 (1-year SNLS. 235 SNIa total).

Constraints from combination of CMB+f_{gas}(z) data

The combination of CMB+f_{gas}(z) data breaks key parameter degeneracies



A) Ω_Λ vs. Ω_m (non-flat)

68.3 and 95.4% confidence:

Blue: CMB only (0.4<h<2.0)

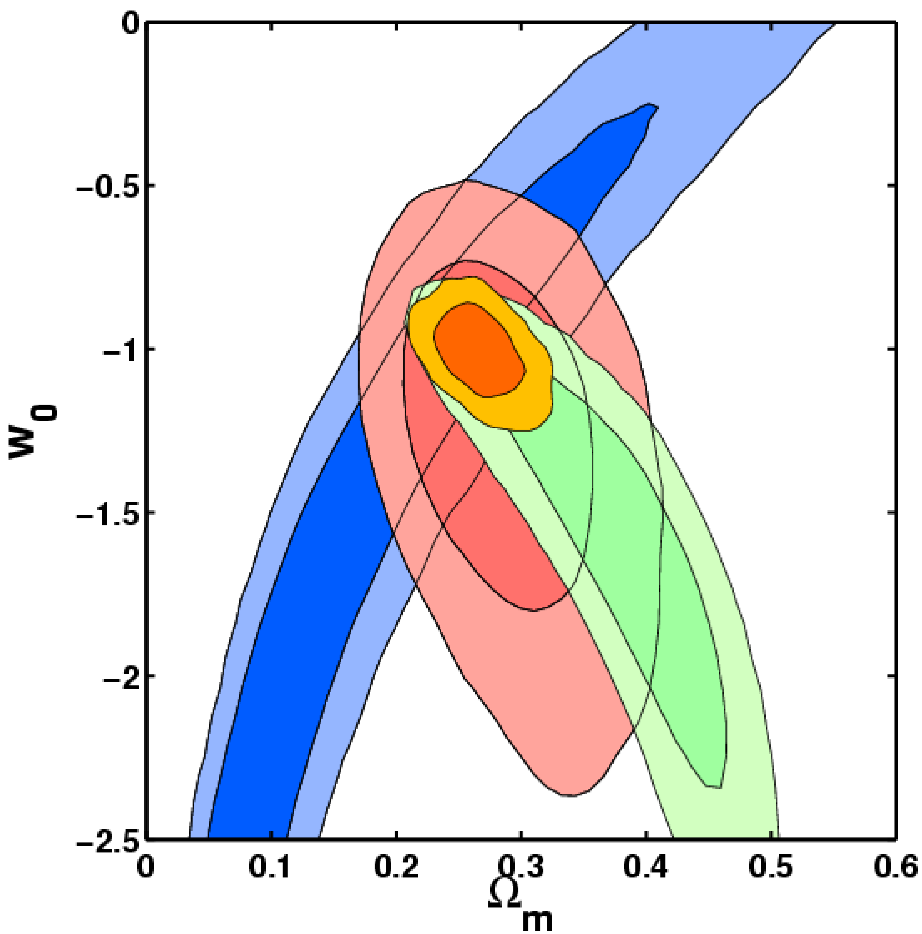
Red: f_{gas}(z)+CMB data

Marginalized results:

$$\Omega_{DE} = 0.73 \pm 0.05$$
$$\Omega_m = 0.27 \pm 0.05$$

Combination with CMB data removes need for $\Omega_b h^2$, h and flatness priors!

Dark energy equation of state:



Allen et al 2007

Constant w model:

Analysis assumes flat prior.

68.3, 95.4% confidence limits for all three parameter pairs consistent with each other.

Combined constraints (68%)

$\Omega_m = 0.267 \pm 0.022$
$w_0 = -1.01 \pm 0.09$

Pink: clusters only
Blue: CMB only
Green: SNIa only
Red/Orange: combined.

Method 2: constraining distances with the combination of X-ray+SZ data

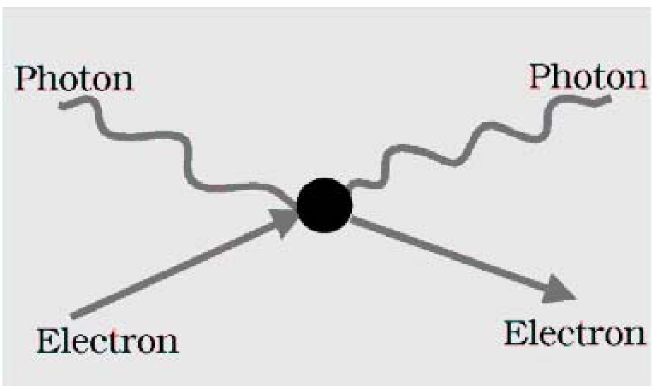
[Rapetti & Allen et al, in preparation]

For more discussion see Molnar et al 2002, Bonamente et al 2006 and references therein.

Absolute distances from combined X-ray + SZ studies

The observed SZ flux (radio/sub-mm data) can be expressed in terms of the Compton y-parameter. For a given reference cosmology, the same parameter can also be predicted from X-ray data.

For correct reference cosmology observed and predicted SZ flux should agree.



$$y_{ref} \propto \int n_e T dl$$

$$y_{ref} = y_{obs} k(z) \left[\frac{d_{ref}}{d_{\text{mod}}} \right]^{1/2}$$

Combined cal.+ systematic uncertainties $k(z)=k_0(1+\alpha_k z)$

To date, experiment only used to constrain H_0 (e.g. Bonamente et al '06)

Intrinsically less powerful than fgas experiment but provides important complementary information and, in combination with fgas data, allows us to minimize the need for priors in the anlaysis (important).

Considerations for instrumentation and observing strategy

FOV and background considerations

In order to measure fgas easily at radii r_{500}(~$0.6r_{vir}$) for z>0.3, we require a field of view of at least 8-10 arcmin in size.

Note: r_{500}~4-5 arcmin for a big cluster at z=0.3
r_{500}~2-3 arcmin for a big cluster at z=0.5
r_{500}~1-2 arcmin for a big cluster at z=1.0

Note that it not necessary to have high spectral resolution across the whole field (few tens of eV may be sufficient). High spectral resolution for the central few arcmin is v. important though to control systematics in mass measurements as well as lots of interesting cluster physics.

PARTICLE BACKGROUND There is great advantage in having the net particle background lower (by factor of a few) than for Chandra/XMM (Bautz update).

SPATIAL RESOLUTION Please give us every bit of spatial resolution possible (important both for identification of relaxed clusters and the exclusion of contaminating emission from AGN). 5” much better than 15” (though we have strategies to work with 15”).

Baseline proposal: fgas(z) and X-ray+SZ studies

Use 10-15% of available time over first 5 years of Con-X mission (12-15Ms).

STEP 1: First take ~1ks snapshots of ~2000-5000 most X-ray luminous (or highest integrated SZ flux) clusters detected from precursor X-ray and/or SZ surveys → identify most massive relaxed systems. (2-5 Ms total time)

STEP 2: A resulting sample of the `best' 250-500 clusters will then be targeted for, on average, 20-40ks each, allowing us to measure fgas and/or predict the Compton y-parameter to 5% or 3.5% accuracy, respectively. Note 5% accuracy in fgas corresponds to 3.3% in distance) (10 Ms total time)

The following results should be achievable….

Set-up of the simulations

We assume that the baseline proposal has been carried out.

Results are presented in the style of the Dark Energy Task Force (DETF) report to allow for direct and easy comparison with other techniques.

Like the DETF, we assume use `Planck priors'.

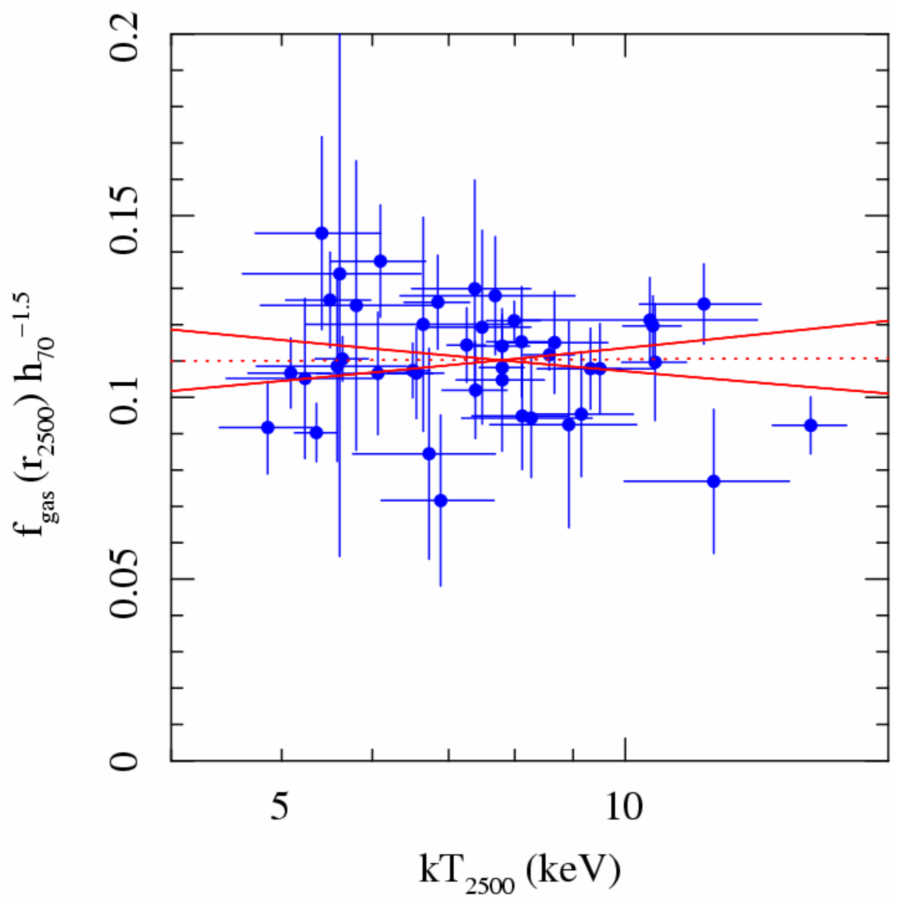
We present results for `standard', `optimistic' and `pessimistic' systematic allowances/uncertainties on priors.

The following results should be achievable….

→ OVER TO DAVID RAPETTI

A few extra words on systematics

A systematic trend of f_{gas} with temperature?



NO, THINGS LOOK GOOD!

Best-fit power-law model is consistent with a constant. (plot shows 2-sigma limits).

We find no evidence for a trend of fgas with kT in the current Chandra data.

Consistent with non-radiative simulations of Eke et al 1998 and Crain et al 2006.

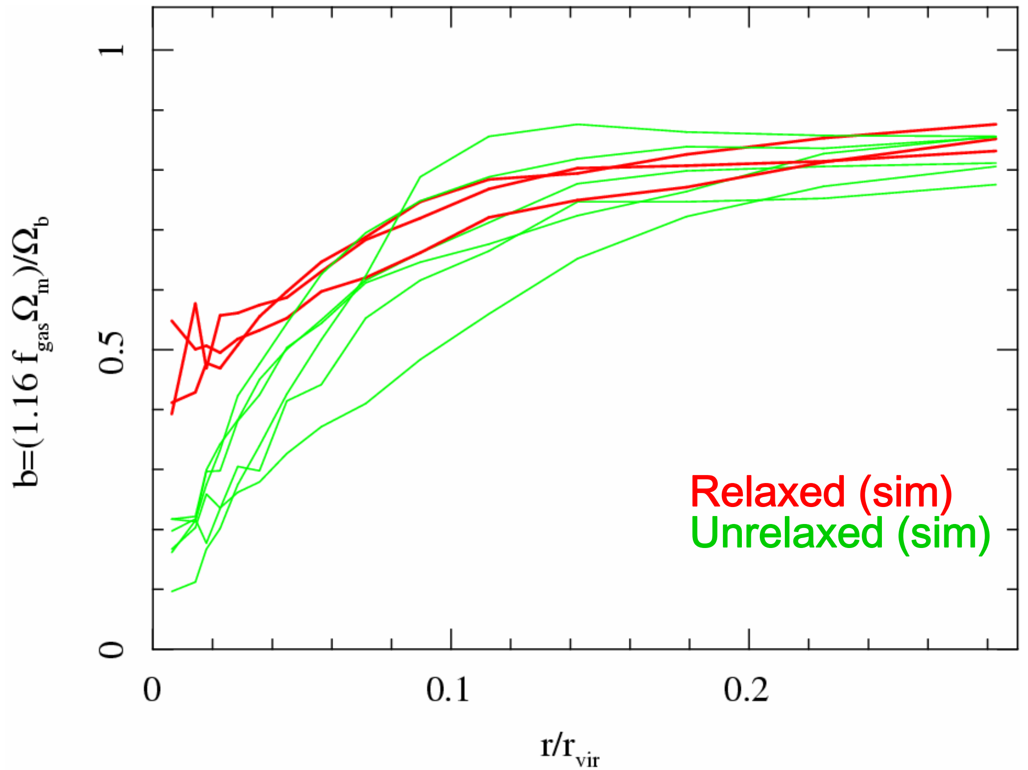
Comparison of observed and simulated fgas profiles

Simulations:

$$f_{\mathrm{baryon}} = b\frac{\Omega_b}{\Omega_m}$$

Note: r_{2500}~0.25 r_{vir}

Eke et al 98



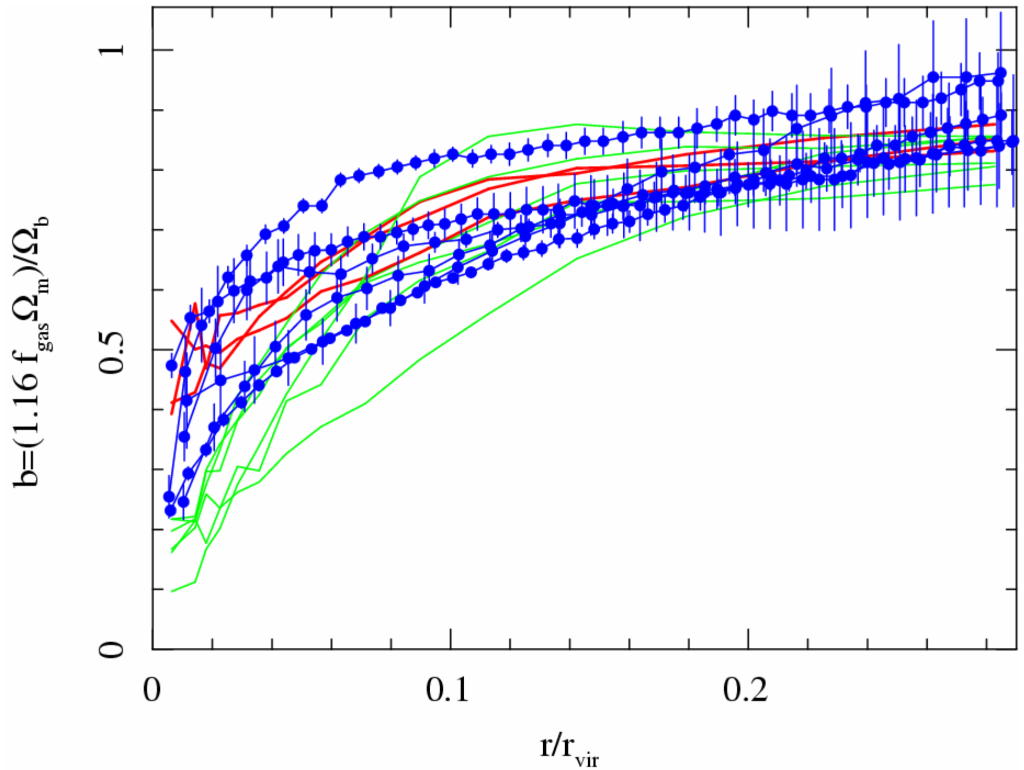
Comparison of observed and simulated fgas profiles

Simulations:

$$f_{baryon} = b \frac{\Omega_b}{\Omega_m}$$

Result is challenging for modified gravity theories with no dark matter.

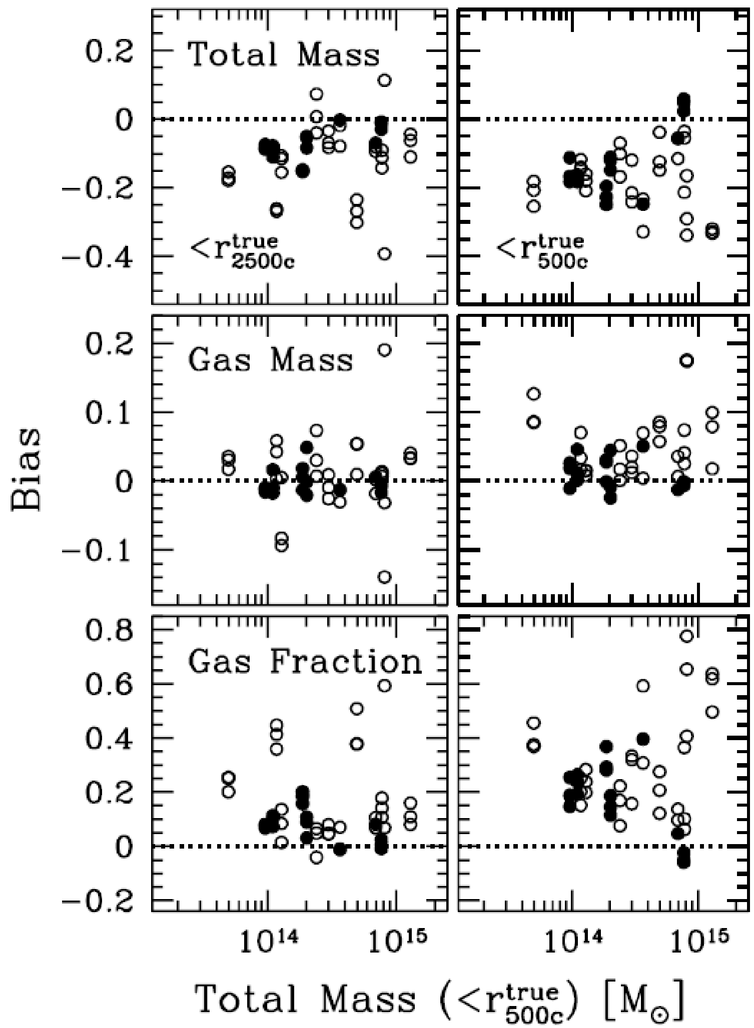
Eke et al 98



Preliminary result: good agreement with non-radiative simulations.

New large hydro simulations (based on Millenium run) including wide range of plausible gas physics underway (Thomas, Kay, Pearce et al.). Should significantly reduce uncertainties associated with prediction of b(z).

What do we expect in terms of systematic accuracy?



Hydrodynamical simulations:

Nagai et al. '06 argue that for massive, relaxed clusters, X-ray determined masses from within r2500 almost unbiased (<8% with upper limit set by viscosity of gas).

Dolag and Schindler '00 argue that for massive, relaxed clusters, magnetic pressure support likely to be negligible (< few %)

Don't expect our main conclusions to be affected by such uncertainties.

But remember that X-ray data used here only extend to ~r2500 and so require factor ~3 extrapolation of NFW models to reach virial radii.